Molten salt facilities, lessons learnt at pilot plant scale to guarantee commercial plants; Heat losses evaluation and correction

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Abstract

This paper presents the importance of the thermal losses in the performance evaluation of thermal storage systems. In order to reinforce this statement, an evaluation of a pilot plant whose size is sufficiently representative for the extrapolation of results at larger scales has been carried out. The evaluation of the heat losses of a molten salt pilot plant with 8.1 MWh_{th} built in Spain by Abengoa is presented. While the storage materials development has attracted a lot of attention from the researchers, the performance of a two-tank storage system has not been evaluated in detail. The relevance of the design of conventional systems such as insulation, mechanical assembly or foundation, are found to be the key for the feasibility of a TES system. Different performance scenarios were performed and based on experimental results, decisions for reengineering of the pilot plant could be taken to improve commercial storage plants.

Key-words

Thermal Energy Storage (TES); molten salt; heat losses; reengineering; lessons learnt; concentrated solar power plant (CSP)

1. Introduction

The mixture known as "solar salt" is formed by a non-eutectic binary mixture of 60%wt. sodium nitrate and 40%wt. potassium nitrate [1,2]. This mixture has a freezing point of 220 °C, making it necessary to keep the system fully insulated and with heat tracing installation to avoid problems. Any problems either in design, mechanical assembly, or other operating systems will cause freezing of the system and to stop operation of the blockade. These systems are designed to counter at all times the inherent thermal losses working at such high temperature. It is very important to calculate these heat losses to ensure the operability of the plant.

Molten storage tank heat losses were first evaluated in the CESA-I central receiver plant in Spain in 1984 [3,4] and latter at the Solar Two project in 2002 [5]. Later on, different authors have estimated the overall heat transfer coefficient giving correlations that consider heat losses [6]. Nevertheless, none of them evaluated local heat losses and thermal bridges in a real molten salts installation.

The aim of the salts pilot plant built in Solúcar (Sevilla, Spain) was the experimentation of the thermal energy storage technology by sensible heat storage with a mixture of molten salts chosen specifically for this project. The storage system has a capacity of 8.1 MWh_{th}, which is 4 hours of the solar power to which was connected; a 600 m solar loop with 2.025 MW_{th} parabolic troughs. The storage system tested was an indirect double tank. In a previous paper [7], the pilot plant is described in detail and the start-up process is analysed and recommendations are given. In this paper, the heat losses are evaluated and corrections are suggested and analysed. Heat losses were evaluated with thermography during the start-up period and with temperature profiles during operation in order to make an energy and exergy analysis. Energy analysis evaluates the energy from a quantitative point of view, whereas exergy analysis assesses the energy on quantity as well as the quality. The aim of the work carried out has been to identify the magnitudes and the locations of real energy losses, in order to improve the existing systems, processes or components in a molten salts double tank configuration thermal energy storage system.

2. Pilot plant description

A very detailed description of the pilot plant can be found in the previous publication [7]. Here only a broad description is given. The installation has two storage tanks connected to a solar field by a heat exchanger. Each tank has 8 m diameter and about 6 m height (4.4 m cylindrical wall) and is able to store all the salts needed in the process. The heat exchanger is a flat plate heat exchanger working at counter-flow with a power of 2.1 MW_{th} and installed following the concept of free-drainage.

The salt used is the so-called "solar salt", a non-eutectic mixture of 40% wt. KNO_3 and 60% wt. $NaNO_3$. This mixture melts at 204 ºC and solidifies at 220 ºC, and it is stable up to nearly 600 ºC. During operation the temperature of the salts changes between 288 ºC and 388 ºC, with a maximum operation temperature of 400 ºC. Usually, in the cold tank the salts are at 288 ºC and in the hot one at 388 ºC.

The tanks were insulated with Spintex 342-G-145 from Isover. The bottom of the tank was protected with Superwool™ 607 ™ blanket from Thermal Ceramics, covered with a galvanized shell. The properties of the insulation materials are presented in Table 1.

Table 1. Characteristics of the insulation materials used in the tanks.

Material	Thickness (mm)	Density (kg/m^3)	Maximum service temperature (ºC)
Spintex 342-G-145	30 to 100	125	750
Superwool™ 607 ™ Blanket	50	128	750

The tanks walls were insulated with two mineral wool blankets with 250 mm thickness. Special care was taken in the non-homogeneous parts, that is, where instrumentation and sensors were located. The insulation material was protected with an aluminium corrugated sheet. The domes of the two tanks were insulated with two 250 mm thickness mineral wool blankets and were protected with aluminium corrugated sheet.

The piping was insulated with 100 mm of mineral fibre insulation Spintex 342-G-145 from Isover for temperatures lower than 649 ºC, and calcium silicate for higher temperatures. All equipment at temperatures higher than 71.1 ºC and at a height lower than 2.134 m over the floor, platforms or corridors, was insulated or protected for persons. All external insulation was protected with aluminium shells. At the design and building of the pilot plant all control elements existing in the piping system were not insulated.

The tanks were supported over two different structures, one over the hot mesh (in direct contact with the storage tanks) and the other in direct contact with the foundations. Both mesh were formed by beams, diaphragms and stiffeners of structural steel ASTM A36. The hot mesh has insulation between the beams to decrease heat losses (Figure 1).

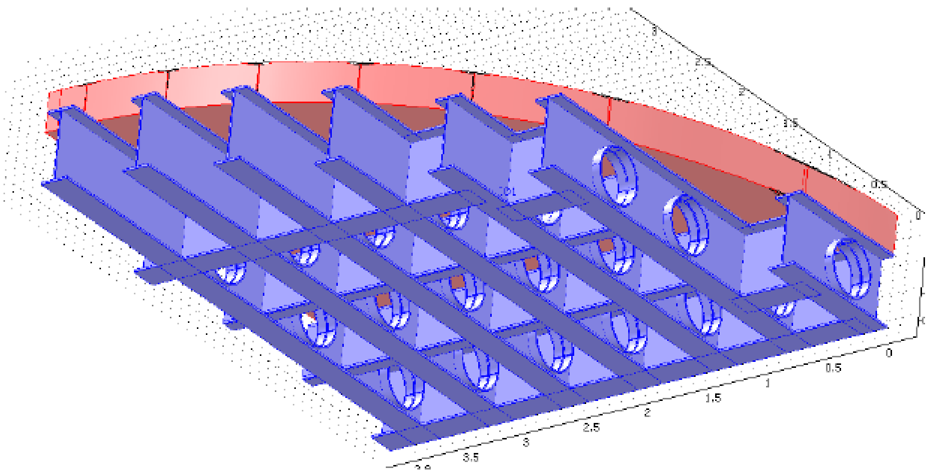

Figure 1. Initial state of tanks support structures and foundation [7].

The first variable that was identified as affecting the rate of conductive heat transfer is the temperature difference between the two locations. The second variable of importance is the materials involved in the heat conduction. The rate of heat transfer depends on the material through which heat is transferred. The effect of a material upon heat transfer rates is expressed in terms of the thermal conductivity and thermal diffusivity.

Another variable that affects the rate of conductive heat transfer is the area through which heat is being transferred. As such, the rate of heat transfer is directly proportional to the surface area through which the heat is being conducted. Finally, a variable that affects the rate of conductive heat transfer is the distance that the heat must be conducted. The rate of heat transfer is inversely proportional to the thickness of the insulation layer.

3. Heat losses during the start-up of the storage pilot plant

3.1. Heat losses in the storage tanks

The process of filling the storage tanks started on a February 14th, 2009 (winter period in Spain). During the first 48 hours of the process, very important heat losses were measured with a thermography camera, mostly located in the wall near the bottom part of the tanks (Figure 2). Figure 2 shows that the metallic beams of the foundation were important thermal bridges and Figure 3 that concentration of the thermal insulation was not homogenous. These layers were reinforced immediately and a protective screen was installed in the south face of the tanks to minimize the wind effect (Figure 4). With this initial correction, the temperature drop rate was reduced 40%. The conductive heat flow of an insulating material is measured or rated in terms of its thermal resistance. The thermal resistance value depends on the type of insulation, thermal conductivity, its thickness, and its density. The effectiveness of an insulating material also depends on how and where the insulation is installed.

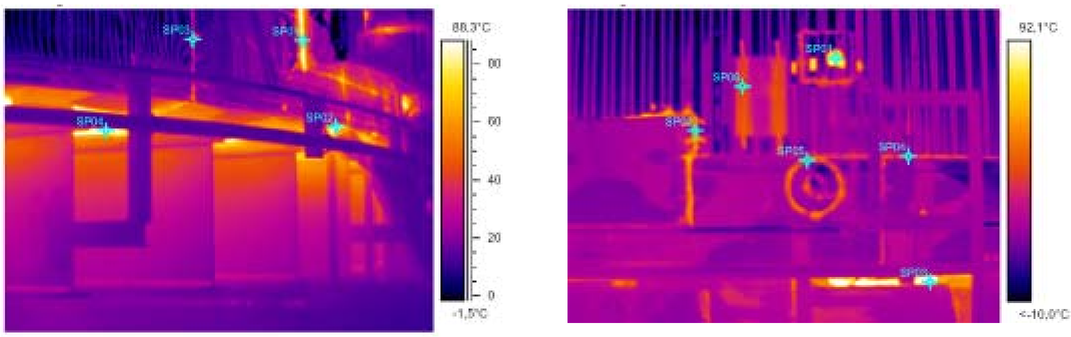

Figure 2. Storage tanks foundation. Left, hot tank; right, cold tank.

Figure 3. Lack of insulation material in the storage tanks.

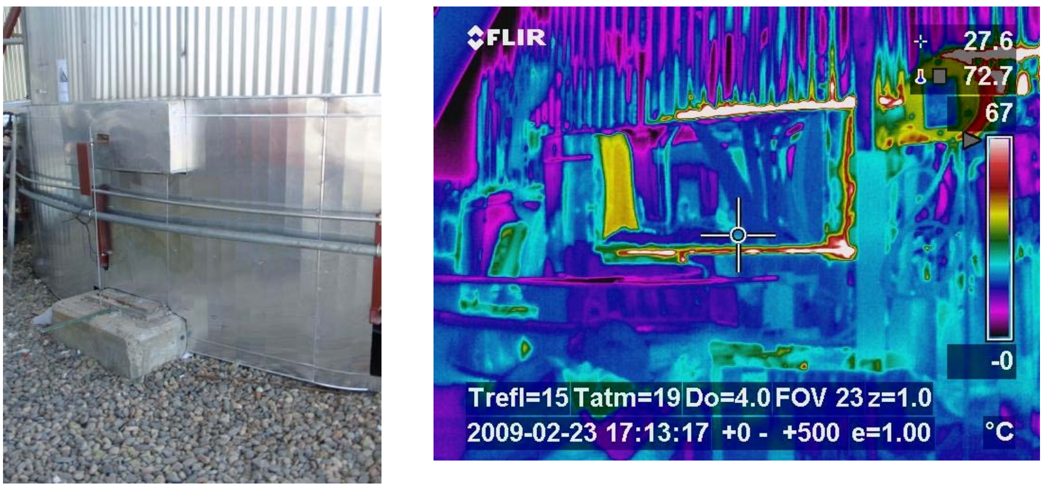

Figure 4. Foundation of the hot tank.

Thermographs showed that even though the thermocouples used to measure the wall temperatures of the tank, were also causing thermal bridging (Figure 5), since their temperature was the same as that of the tank. In junctions between the storage tank wall and cover with insulation of both areas done independently, again thermal bridges were detected. The shell used to cover the insulation of the walls was a corrugated steel sheet, while that of the bottom of the tank was flat. Not surprisingly, due to the complexity of the union and to the high working temperatures, thermal bridges appeared in this area also. Moreover, some areas of the tank support structure were not insulated, showing important thermal bridges afterwards.

The thermal bridge occurs when there is a gap between materials and structural surfaces. The main thermal bridges are found at the junctions, instrumentations or other singularities in the layers of insulations. In a plant that is not properly insulated, thermal bridges represent low comparative losses (usually below 20%) as total losses via the walls. However, when the walls are very well insulated, the percentage of loss due to thermal bridges becomes high (more than 30%). It is important to have very high thermal resistances for walls, foundations and connexions to have low heat losses via the junctions.

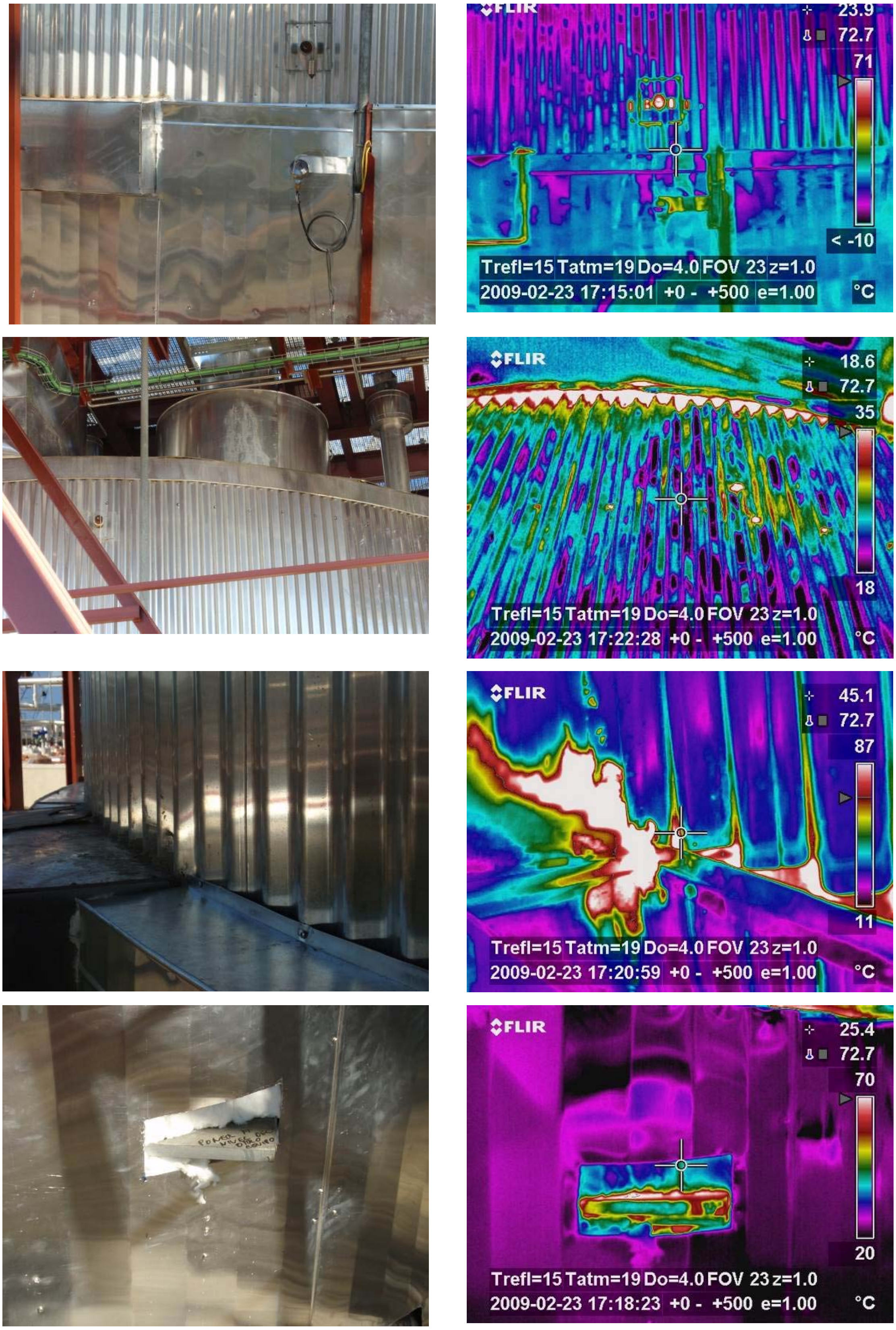

Figure 5. Heat losses in the tank. From top to bottom: thermocouples at the wall; top junctions; bottom junctions; and support structure.

3.2. Heat losses in the piping and heat exchanger

During the pre-commissioning of the plant the preliminary detected heat losses were reduced and after the filling of the tanks with molten salts, circulation between both tanks started. After 24 h of operation, significant heat losses were detected again but now in the piping and in the heat exchanger.

Figure 6 shows that, similarly to what happened in the tanks, most thermal bridges appeared in the unions of pipes with different diameter, probably due to thermal expansion. To reduce heat losses the pipe insulation must overlap the box that contains the pipe fittings. Important heat losses were detected again in connections between piping and supports.

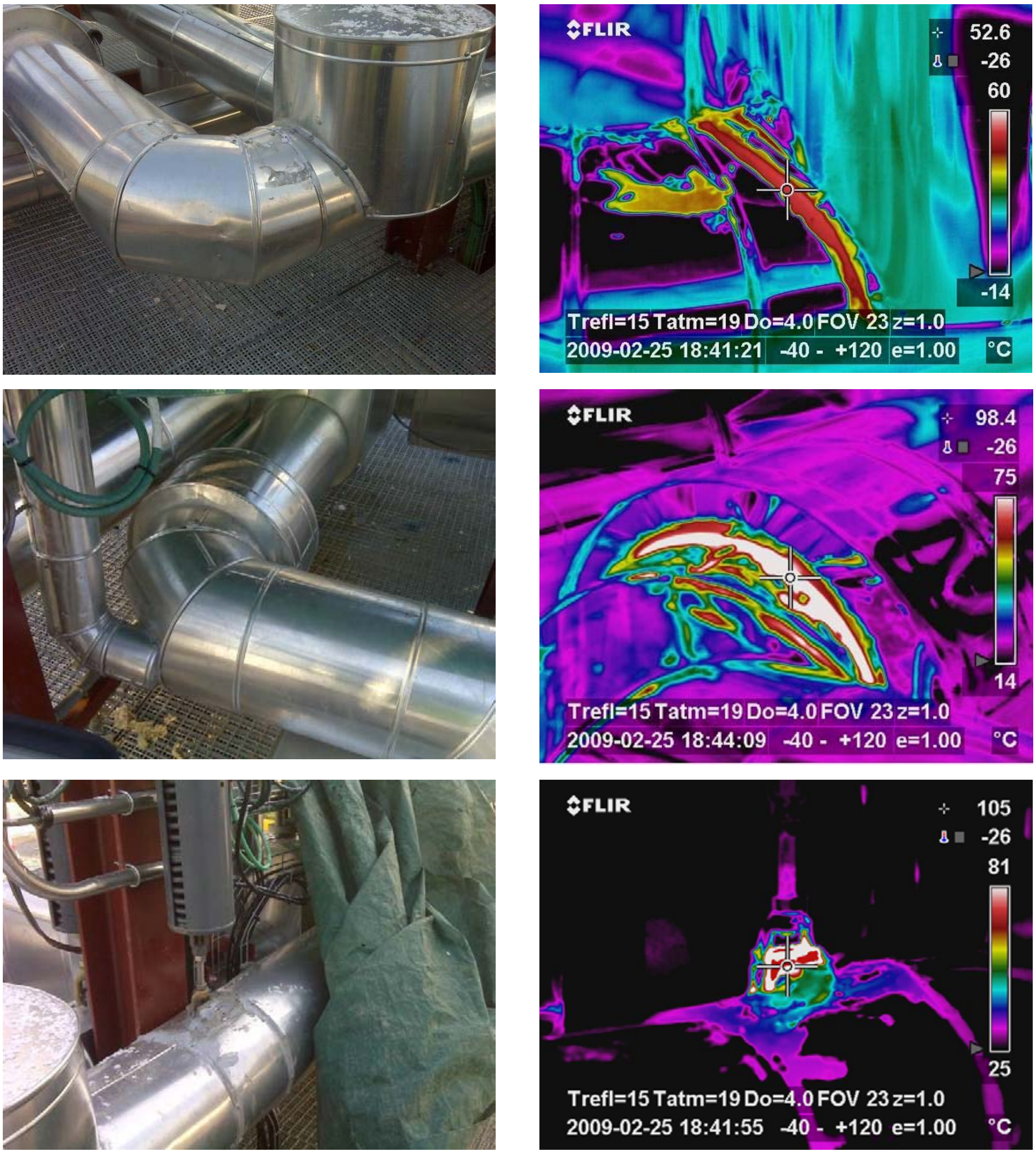

Figure 6. Piping, joints and piping support evaluation.

Once more, important thermal bridges were found in the auxiliary equipment, the instrumentation, valves, and supports and shoes in the molten salts piping (horizontal), the supports and shoes in the thermal oil piping (vertical), and the heat exchanger (Figure 7).

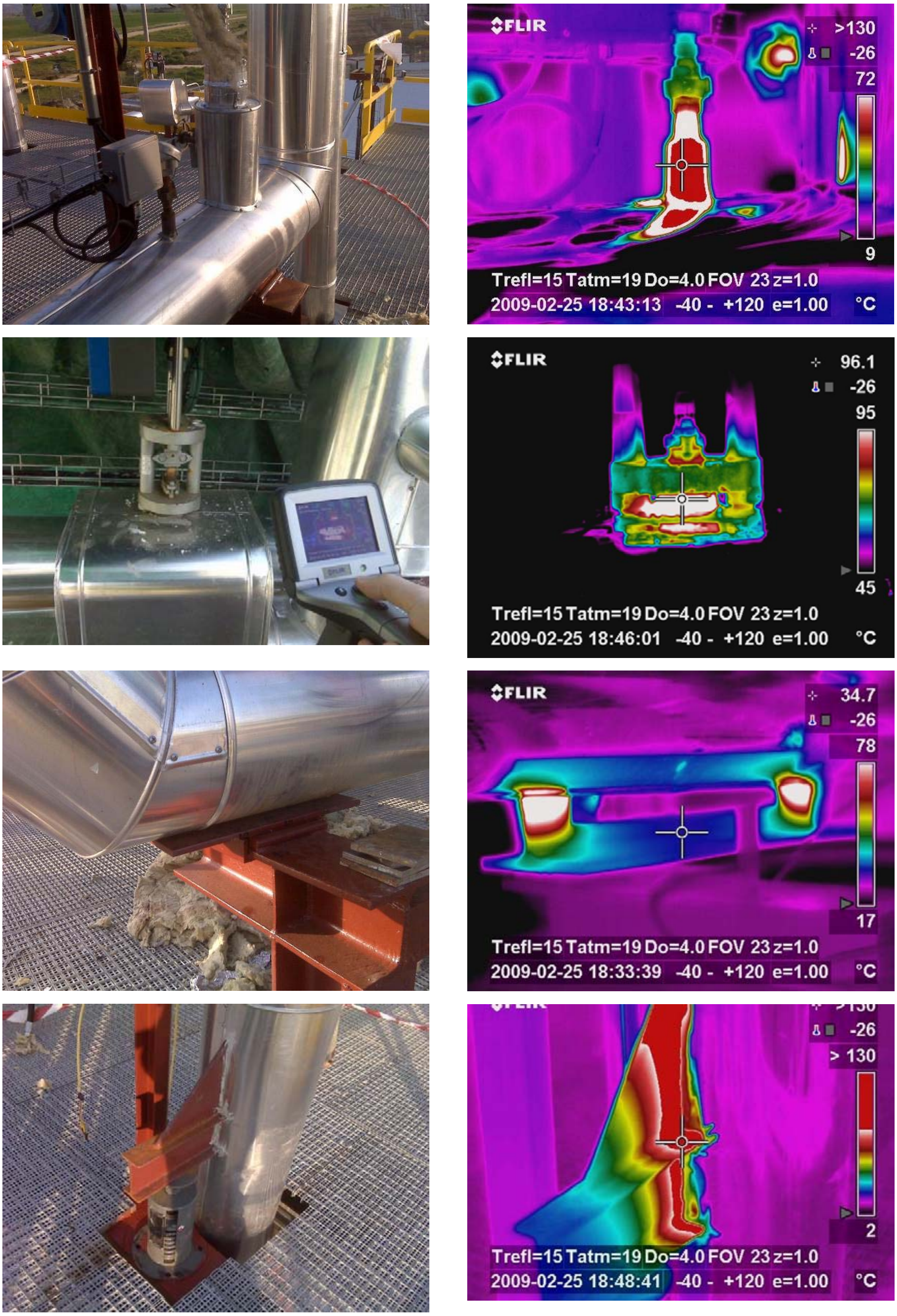

Figure 7. Heat losses in auxiliary equipment. From top to bottom: piping instrumentation; valves; molten salts piping support; oil piping support; and heat exchanger.

To reduce the heat losses in the piping supports, the following measures are recommended:

- To install insulation between the pipe and the clamps in the support. The insulation to be used here is the same one installed in the trough solar collectors between the solar collector pipe and the clamps in the supporting structures. Nevertheless, more research and testing are needed to ensure that this material can support the thermal cycles of the pipes without breaking down or losing position.
- To consider the support as part of the pipe and therefore insulate it completely. In this case, in the contact point between the support and the pipe an insulating material with the appropriate thermal and mechanical properties should be included (i.e. Syndanio [8], a thermal and electrical insulation consisting of ceramic-non asbestos board). This second option needs an economical evaluation due to the high price of a material such as Syndanio.

3.3. Heat losses in the clamp shoes

The oil circuit piping also had important heat losses, mainly in the clamp shoes. A ceramic fibre coating was installed in all the shoes (Figure 8) and a more rigid insulation material in the contact points between the shoes and their support structure (Figure 9). The molten salts pipes shoes were insulated with 10 mm of Syndanio [8], Figure 10 shows the flux of energy in the clamp shoes.

Figure 8. Shoes clamps with ceramic fibre

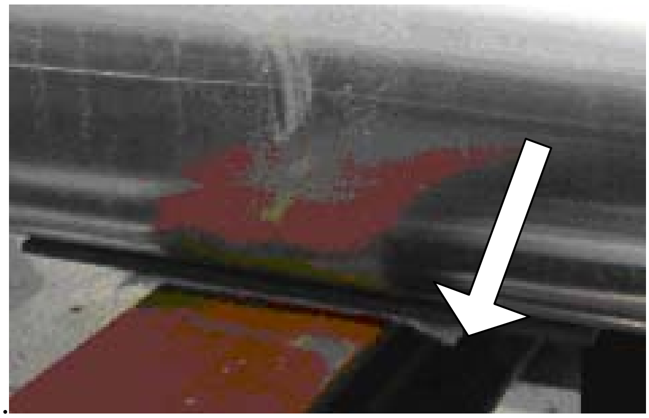

Figure 9. Detail of fiber gasket to break thermal bridge in shoes

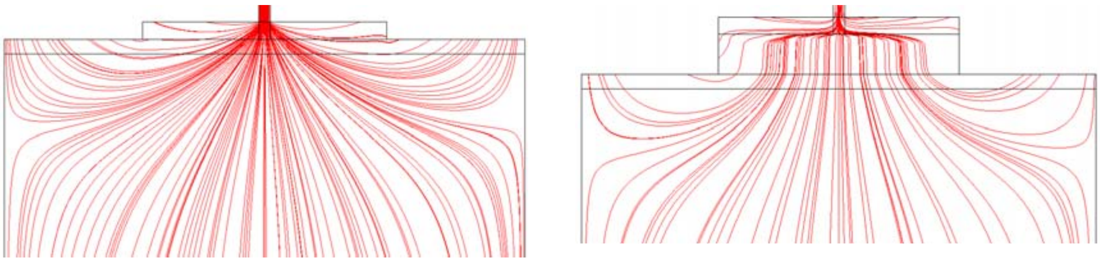

Figure 10. Shoes flow lines. Left: shoe directly on the support; right: shoe mounted on Syndanio

4. Analysis of the thermal losses of the installation

4.1. Modelling the heat losses in the foundations

Heat losses of molten salt tanks were analysed with the available data, and reengineering solutions were looked for to avoid or minimize the risk of salts solidification during long periods without sun. One further aim was to avoid high temperatures in the concrete base (maximum 100 ºC were allowed).

The foundation scheme is shown in Figure 1, and its positioning on the concrete slab in Figure 11. The hot mesh, closer to the tank, was full of thermal insulation, while the cold mesh was isolated from the ambient air but was still empty, therefore natural convection was possible.

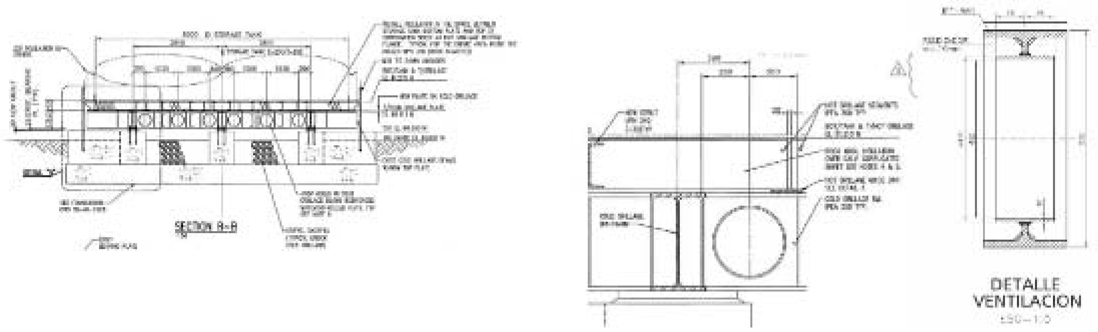

Figure 11. Foundation mesh section

The heat losses were modelled considering a semi-infinite model [9,10], with an initial temperature of 370 ºC and 100 hours without sun input, simulating several days without sun. The emissivity of the galvanized screens for radiation was considered to be 0.23 for the new screen and 0.88 for the used one [11]. The temperature of the galvanized screen was estimated from thermography measurements (Figure 12). Considering that the average temperature of the screen is 70 ºC, and that the emissivity of the mesh 75% that of the screen (Eq. 1), the average temperature of the mesh is 95.5 ºC.

$$\varepsilon_{screen} = \frac{T_{screen}^4}{T_{grading}^4} \cdot \varepsilon_{grading} \qquad \text{(Eq. 1)}$$

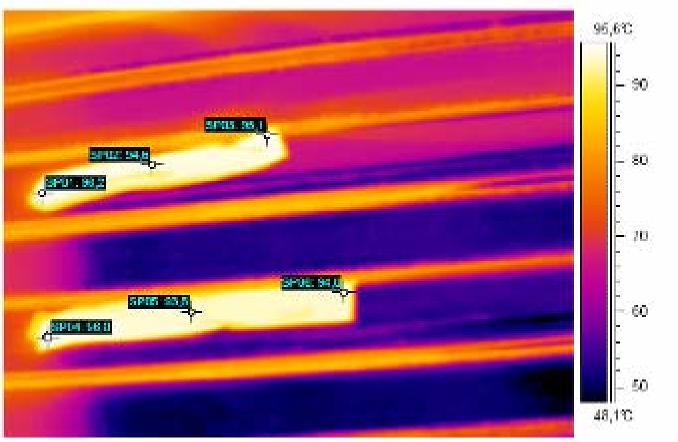

Figure 12. Surface temperature of the galvanized screen located next to the hot mesh

To find the best option to decrease heat losses through the mesh, different scenarios are set, changing the type of insulation material in the cold mesh and the thermal conditions of the tank. The temperature dependence of the screen with the mesh and the tank is assumed as:

$$T_{screen} = \tfrac{1}{3} \cdot T_{\text{tank}} + \tfrac{2}{3} \cdot T_{\text{ambient}} \qquad \text{(Eq. 2)}$$

To consider the heat losses from the tank to the air by radiation and convection, the surface temperature of the tank is estimated by:

$$T_{\text{tank surface}} = \frac{1}{6} \cdot T_{\text{tank}} + \frac{5}{6} \cdot T_{\text{ambient}} \qquad \text{(Eq. 3)}$$

The tank dimensions are 8 m diameter [7] and 6 m height. The hot tank (considered at salts at 370 ºC) is considered to have 1/6 height full with molten salts, the cold one (considered at salts at 300 ºC) to have 5/6 height full.

Heat transfer through the concrete base to the floor is calculated with [9,10]:

$$Q_{floor} = k_{floor} \cdot \left(\frac{T_{concrete} - T_{floor}}{\sqrt{\pi \cdot \alpha_{floor} \cdot t}} \right) \qquad \text{(Eq. 4)}$$

The considered materials for the calculations are mineral wool for the insulation and stainless steel AISI302 for the tank. The thermal conductivity of mineral wool is calculated with:

$$k_{\text{mineral wool}}\left[W / m \cdot {}^{\circ}C\right] = \left(0.000156 \cdot T\left[{}^{\circ}C\right] + 0.0291\right) \qquad \text{(Eq. 5)}$$

The properties of the concrete base and the floor (sandstone) are presented in Table 2.

Table 2. Data of materials for scenarios simulation.

Material	**Temperature [ºC]**	**Thermal diffusivity (α) [m²/s]**	**Density (ρ) [kg/m³]**	**Thermal conductivity (k) [W/m·ºC]**	**Specific heat (Cp) [J/kg·ºC]**
Concrete	27	$6.92 \cdot 10^{-7}$	2300	1.40	880
Rock (granite)	27	$1.37 \cdot 10^{-6}$	2630	2.79	775
Sand	27	$2.23 \cdot 10^{-7}$	1515	0.27	800
clay	27	$1.01 \cdot 10^{-6}$	1460	1.30	880

The conditions considered in the modelling are:

1. Summer, hot tank at 370 ºC during 8 hrs – simulation of full thermal charge in the storage tank.
2. Winter, tank discharged and with no heater, starting at 300 ºC, during 100 hrs – simulation of discharged tank and with no sun input. The aim of this simulation is to find out when the salts reach their solidification temperature.
3. Winter, tank discharged and with heater on, starting at 300 ºC, during 100 hrs – simulation of discharged tank and with low sun input, enough to maintain the salts at the "cold salts temperature".

The solutions considered to reduce heat losses are also three:

a. Adding a radiation screen in the cold mesh, next to the insulation material.
b. Metal plate added in the base of the cold mesh.
c. Adding thermal insulation material.

These conditions and solutions were modelled in different scenarios presented in Table 3. Scenarios 3 to 5 had the objective to evaluate the time needed for the salts to start freezing in winter and without possibility of heat input. Scenarios 6 to 8 aimed to evaluate the heat power needed to maintain the salts temperature in winter with the different cold mesh improvement systems considered.

Table 3. Considered scenarios.

#	Tank temperature [ºC]	Floor temperature [ºC]	Ambient temperature [ºC]	Time [hrs]	Thermal behaviour within the cold mesh	Auxiliary heater
1	370	20	40	8	Stratified air (conduction)	No
2	370	20	40	8	Air convection (1 and 10 $W/m^2{\cdot}K$)	No
3	300	5	0	100	Air convection (1 $W/m^2{\cdot}K$)	No
4	300	5	0	100	Radiation screen	No
5	300	5	0	100	Thermal insulation	No
6	300	5	0	100	Air convection (1 $W/m^2{\cdot}K$)	Yes
7	300	5	0	100	Radiation screen	Yes
8	300	5	0	100	Thermal insulation	Yes

4.2. Results

Figure 13 shows an example of the results obtained for scenario 1. The heat losses in the base of the tank are due to radiation, while heat losses to the ambient are higher than those through the concrete base.

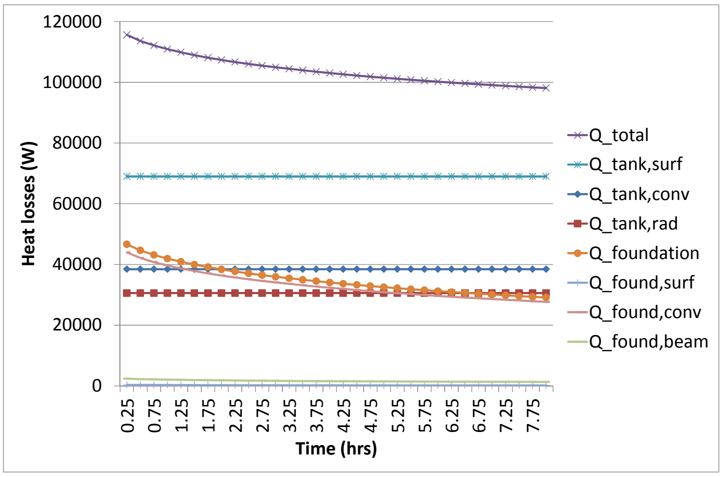

Figure 13. Results for scenario 1.

A comparison of the simulated scenarios would give the right decision for reingeniering of the pilot plant. Scenarios 1 and 2 had the aim to determine the concrete heating risk in summer conditions and with the tank at its higher temperature (Figure 14). As expected, lower losses are found with scenario 2, but in all studied cases the concrete base reach high temperatures (higher than 70 ºC).

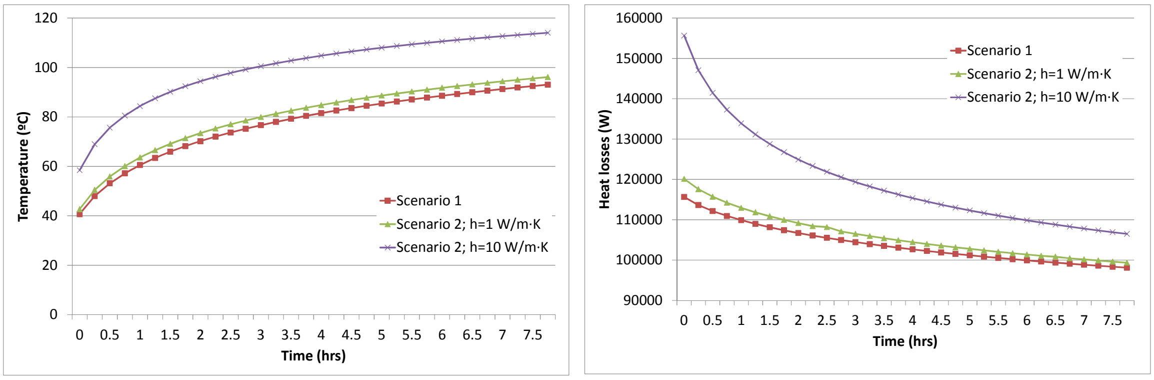

Figure 14. Comparison of scenarios 1 and 2. Left: temperature profile; right: heat losses profile.

The study for winter season when several days without sun can take salts to solidification, scenario 5 gives the best results and scenario 3 the worst (Figure 15). Lower heat losses with lower temperature in the concrete slab and best temperature performance of the salts are achieved when thermal insulation material is added in the cold mesh at the base of the tanks.

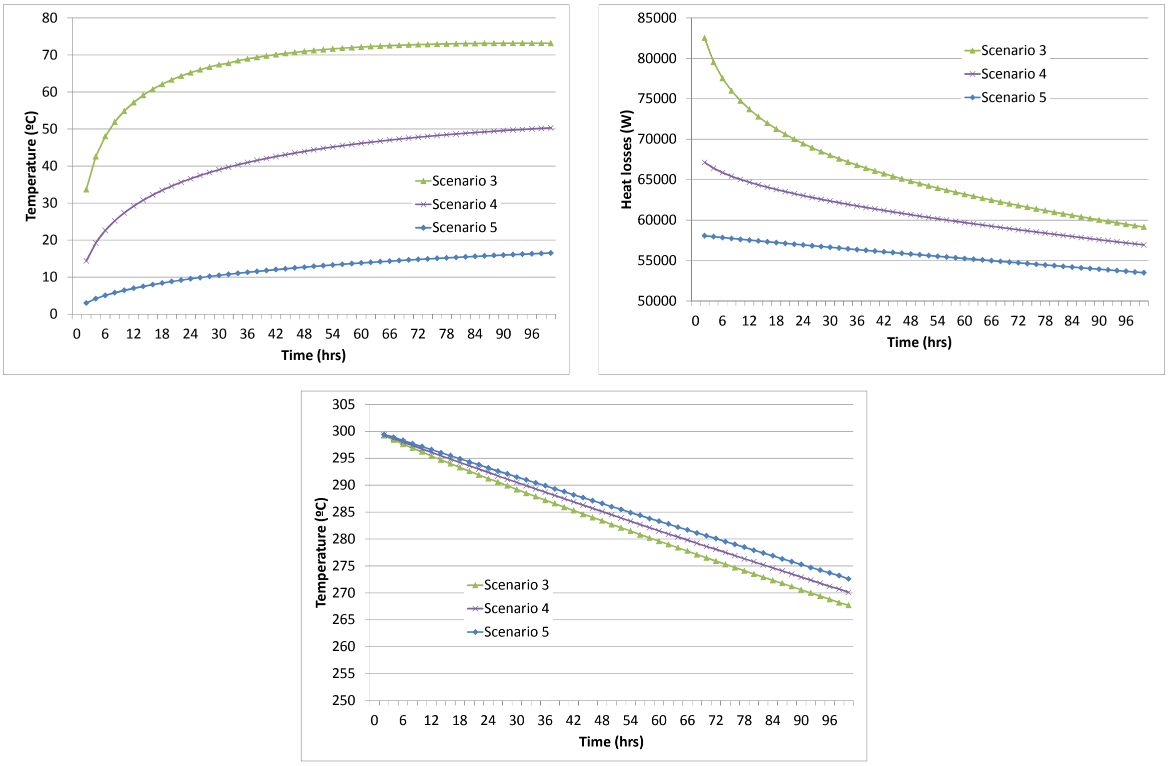

Figure 15. Comparison of scenarios 3, 4 and 5. Left: concrete temperature profile; right: heat losses profile; bottom: tank temperature profile.

The evaluation of the thermal power needed to maintain the salts at the desired temperature (assumed 300 ºC) again shows that the best is to add insulation in the cold mesh (Figure 16). The required maximum thermal power is 82.6 kW_{th} for scenario 6, 67.2 kW_{th} for scenario 7, and 58.1 kW_{th} for scenario 8.

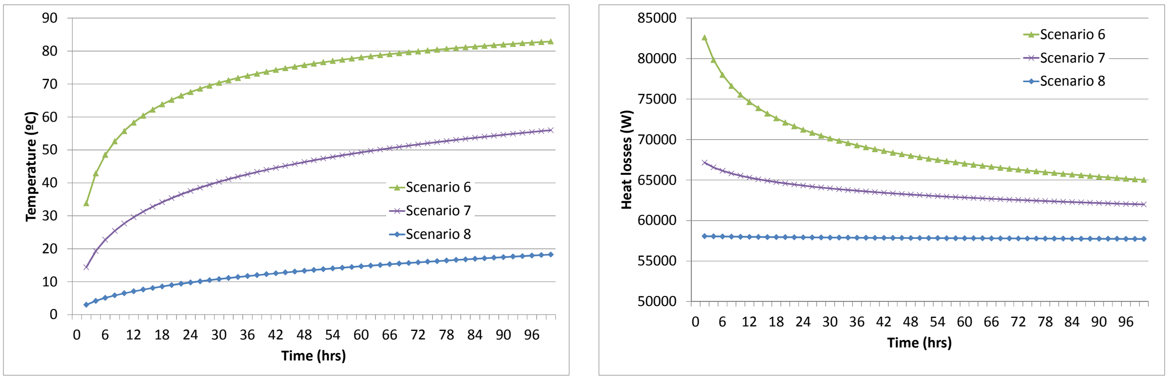

Figure 16. Comparison of scenarios 6, 7 and 8. Left: concrete temperature profile; right: heat losses profile.

4.3. Reengineering

After the scenarios simulation, the approach followed to reduce heat losses in the pilot plant was the addition of a radiation screen in front of the cold mesh of the tanks support and the addition of mineral wool inside it. The conditions considered before were simulated again and the results are discussed below.

The conditions of winter (ambient temperature 5 ºC, floor temperature 0 ºC), with the tank cold (300 ºC) and with auxiliary heater when insulation material is added in the cold mesh are presented in Figure 17, and when also a radiation screen is added is shown in Figure 18. The reduction of heat losses in this last scenario is very high compared to the initial conditions (from 80 kW in scenario 3 to 50 kW and 30 kW in both reengineering scenarios).

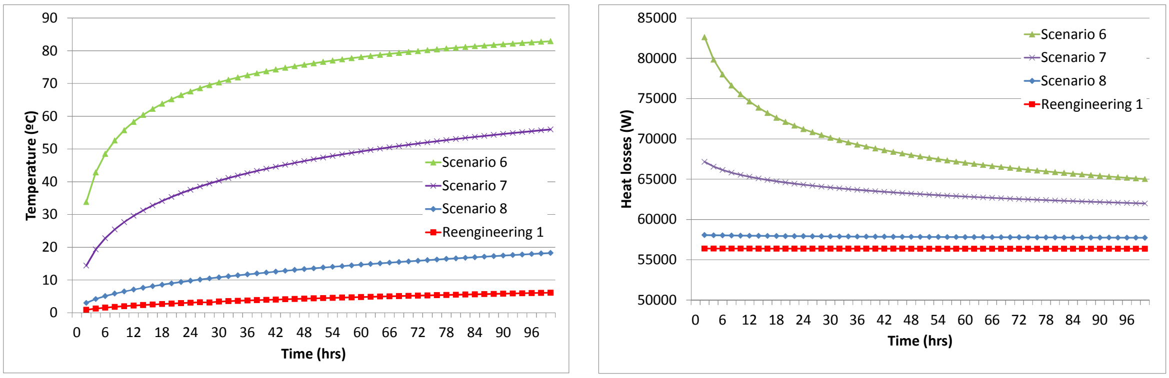

Figure 17. Comparison of reengineering 1 with scenarios 6, 7 and 8. Left: concrete temperature profile; right: heat losses profile.

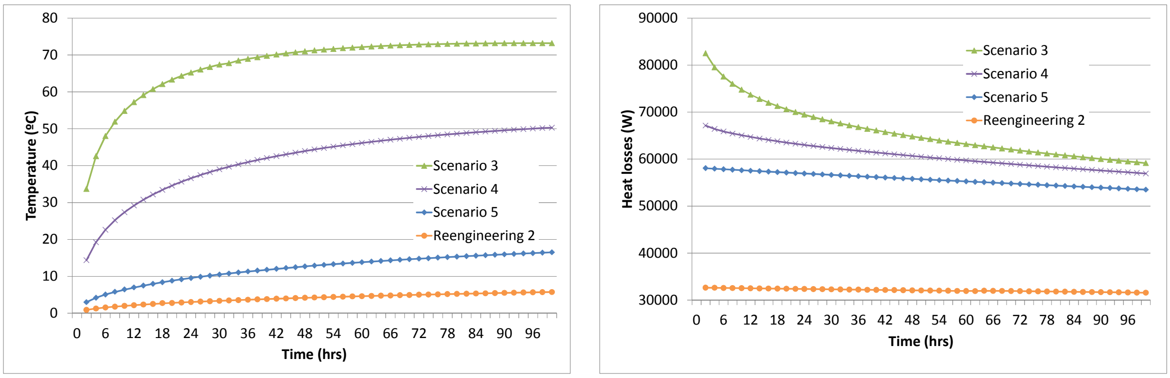

Figure 18. Comparison of reengineering 2 with scenarios 3, 4 and 5. Left: concrete temperature profile; right: heat losses profile.

5. Conclusions

During the first 48 hours of operation of the MS-TES molten salts storage plant installed in Seville in Abengoa premises, important heat losses were measured, much higher than expected from the plant design. The evaluation of such losses brought important knowledge to be learnt.

Thermal bridging occurs in facilities envelopes when materials with high thermal conductivity, such as steel, concrete or even timber, create pathways for heat loss that bypass thermal insulation. Thermal bridging can also take place when gaps or breaks in the insulation envelope create pathways for heat loss that by pass thermal insulation.

A thermal bridging analysis should be done in the pre-commissioning of the power plant. All the foundation of the tank had to be designed to ensure lower heat losses.

Moreover, all the insulation on the tanks, piping, sensors and actuators had to be designed with this criterion on mind. Working at this high temperature, all sensors and actuators must be carefully insulated and it is critical to avoid the contact between the piping and its support at the shoes; in this plant a ceramic fibre coating (Syndanio) is recommended.

To evaluate the heat losses and to find the best approach for future commercial plants, a simulation of the tanks foundation was carried out and different scenarios were evaluated. The first scenarios showed that the actions needed were within the cold mesh of the foundation. Next, it could be corroborated that the addition of a radiation screen would be a good solution, but the best one is to add insulation material within the cold mesh. This last approach would be also the best solution to maintain the temperature of the molten salts reducing the maintenance costs, and giving better storage plant efficiency.

Taking into account the relevant information taken from pilot plants and the size factor in the estimation of the heat losses, higher amount of salt per tank will optimize the losses due to higher ratio of surface per unit volume. These findings have done that current designs in commercial plant have less than 1% of heat losses in the thermal storage system.

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